EXHIBIT A

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Cooling High Heat Flux Devices with *Mikros* Microchannel Heat Sinks

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Summary

Mikros offers liquid-cooled heat sinks for applications requiring high heat flux cooling and low thermal resistance. Our patented Normal Flow Heat Sinks (NFHS) can cool devices dissipating as much as 1000 W/cm^2 with a thermal resistance per unit area as low as 0.05 °C/(W/cm^2). A unique feature of the NFHS technology is the ability to eliminate "hot spots" by matching the local thermal resistance of the heat sink to the local heat dissipation of the device being cooled. This capability enables isothermal operation of devices having non-uniform heat dissipation. Demanding applications that would benefit from this cooling technology include: high-end server microprocessors, power electronic components, and high power lasers, to name a few.

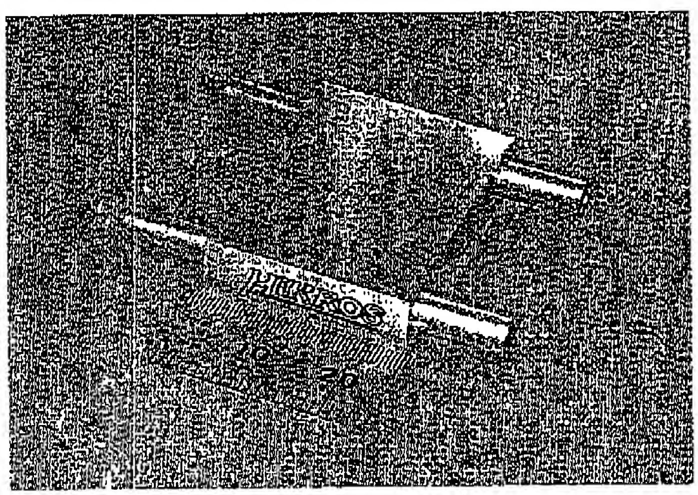

Figure 1. Normal Flow Heat Sink (NFHS)
Active Area: 20 x 20 mm
Thermal Resistance 0.02 °C/W

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3. Comparison with other Liquid-Cooled Cold Plates

This section presents a comparison of the NFHS performance relative to other liquid-cooled cold plates. We include the performance obtained from the vendor literature (water as coolant) for a standard swaged tube aluminum cold plate and two high performance, specialty cold plates:

- *Swaged tube cold plate*: 2.25"x2.4" aluminum cold plate cooled by a double pass 3/8" diameter copper tube.
- *HP aluminum cold plate*. Aluminum extrusion with a closely packed array of small diameter openings in a parallel flow arrangement.
- *HP copper cold plate*. High performance copper cold plate with machined offset fins.

We also include in this comparison the data from the pioneering microchannel heat sink experiments performed by Tuckerman and Peace[2]. That heat sink had 50 μ wide, 300 μ tall microchannels etched into a silicon wafer with an active cooling area of 1 x 1 cm.

The key performance parameter of a cold plate is its thermal resistivity, defined as the temperature rise of the cold plate heat acquisition surface per unit heat flux absorbed. In this comparison the units of the thermal resistivity are: °C/(W/cm^2). The actual thermal resistance in a specific application can be obtained by dividing the resistivity by the cold plate area. That is, if a 2 x 2 cm cold plate has a resistivity of 1 °C/(W/cm^2), its thermal resistance would be 0.25 °C/W.

Figure 7.A compares the range of resistivity values that can be achieved with different cold plates. The dashed line on the figure represents the theoretically optimal cold plate performance (lowest resistivity) for a given liquid flow rate. To achieve this performance, the liquid exit temperature would need to be equal to the maximum temperature on the surface of the heat sink. That is, the fluid temperature rise would be equal to the approach temperature difference and the heat sink effectiveness would be equal to 1.

Figure 7.B compares the pressure drop, and Figure 7.C the thermal effectiveness, of the various cold plates as a function of the thermal resistivity.

These results show the remarkable performance of the NFHS. Again, the main benefits of the NFHS are:

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[2]Tuckerman, D. B. and Pease R.F.W., "High Performance Heat Sinking for VLSI", IEEE Electron Device Letters, Vol. EDL-2, 1981, p 126-129.

- ***Very low thermal resistance.*** Its thermal resistivity is a factor of 2-10 lower than other high performance commercial cold plates and approaches the performance of an ideal cold plate. Its resistivity is even 30% lower than that of microchannels etched on silicon.
- ***Low pressure drop.*** The NFHS achieves this low resistivity with very low pressure drops, especially when compared to other microchannel cold plates.
- ***High Effectiveness.*** The effectiveness of the NFHS is several times higher than that of other cold plates. This means that for a given heat load, the flow rates are correspondingly lower and the fluid temperature rise correspondingly higher. The higher fluid temperature rise and lower flow rate greatly simplify the task of dissipating the heat to the atmosphere, the ultimate heat sink for most applications.

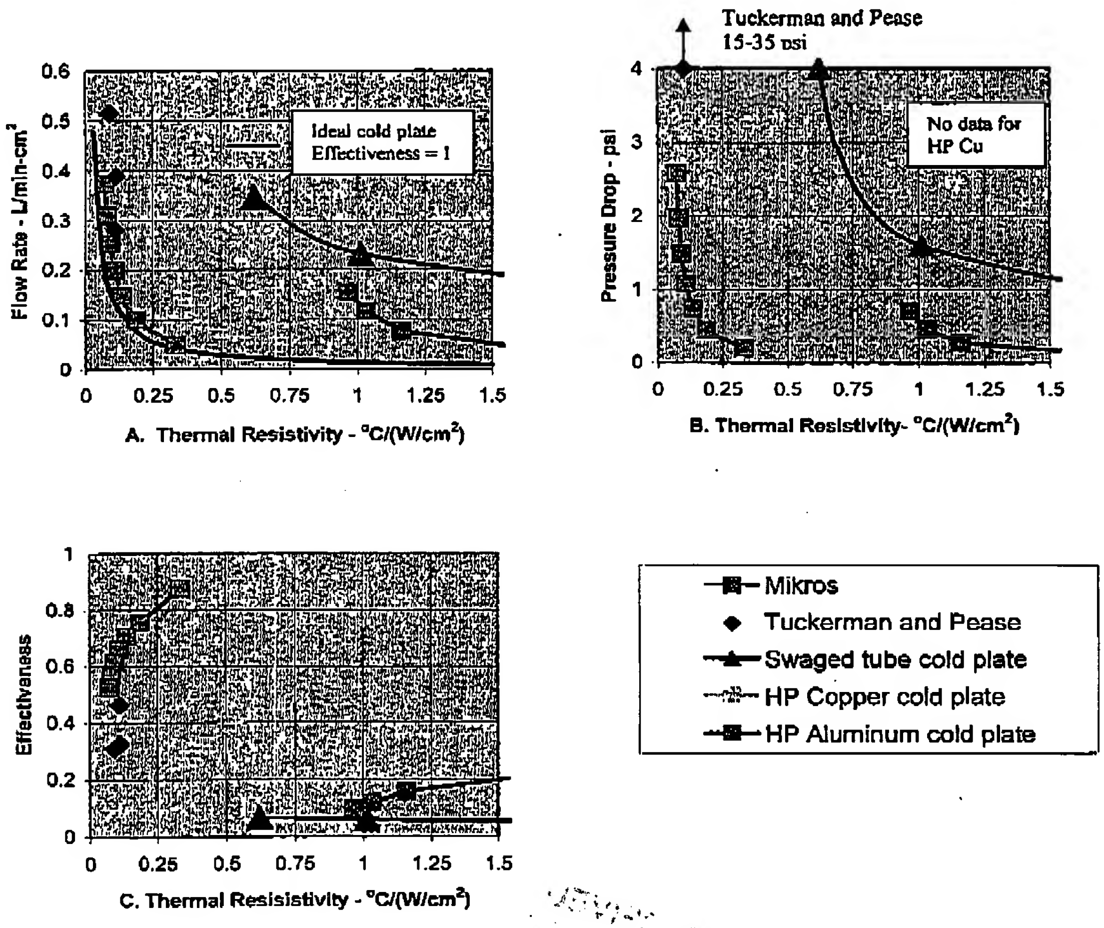

Figure 7. Liquid Cooled Cold Plate Performance Comparison

4. Normal Flow Heat Transfer

The outstanding heat transfer performance of the NFHS derives from a unique arrangement of the microchannels and internal manifolds that promote normal flow heat transfer. This flow arrangement was first described in U.S. Patent 5,029,638[3]. Patents are pending on recent improvements to the original normal flow heat exchanger concept. These improvements form the basis of Mikros' NFHS technology.

Figure 8 illustrates the difference between a standard microchannel cold plate and a normal flow cold plate. Both cold plates have an array of closely spaced fins that define microchannels. In the standard cold plate, the fluid enters on the left hand side and absorbs heat as it flows between the fins towards the exit manifold placed on the right hand side of the cold plate. The flow direction is parallel to the heat acquisition interface. The corresponding temperature distributions on the fluid and the fins are shown on the left hand side of Figure 8. It is assumed in this example that the heat flux is uniform over the surface of the cold plate, as indicated by the uniform temperature drop across the base of the cold plate. The temperature at the base of the cold plate, however, is not uniform because the fluid is heating up as it moves along the passages. The temperature of the fluid leaving the microchannels is also not uniform since the fin temperature will be cooler further away from the base of the cold plate.

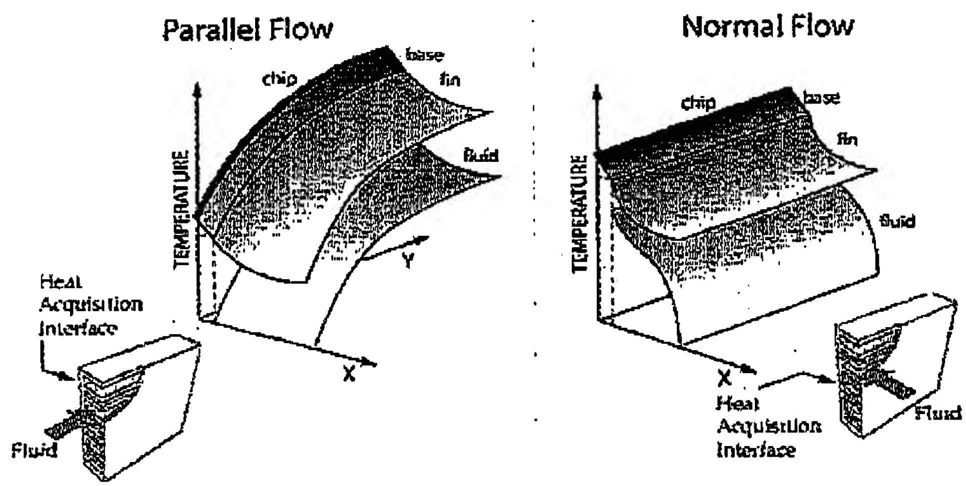

Figure 8. Parallel vs. Normal Flow Cold Plate Temperature Distributions

[3] Valenzuela, J. A. "High Heat Flux Compact Heat Exchanger Having a Permeable Heat Transfer Element", U.S. Patent 5,029,638; 1991.

The normal flow arrangement is illustrated on the right hand side of Figure 8. In this configuration, the fluid enters on the top of the fins and flows between the fins towards the heat acquisition interface, where it is collected in distributed manifolds (not shown in the Figure). The flow direction is normal to the heat acquisition interface. The resulting fluid and fin temperature distributions are shown on the right hand side of Figure 8. In the normal flow arrangement both the temperature at the base of the cold plate and the exit fluid temperatures are uniform over the surface of the cold plate, in contrast to the variable temperatures in the parallel flow arrangement.

The principal characteristics of the normal flow arrangement are:

- ***Local heat transfer is independent of heat transfer in other regions of the cold plate.*** In the parallel flow arrangement the cooling ability of the flow is continually decreasing along the length of the channel. Hence, the wall temperature near the exit side is higher than near the entrance side. In the normal flow arrangement, each region of the cold plate receives fluid at the same temperature. This means that the cooling potential is the same throughout the surface of the cold plate. It also means that one can change the local resistivity in one region by varying the local flow rate, without affecting other regions of the cold plate.
- ***Low fluid velocities.*** In the parallel flow arrangement, all the flow must travel through the thin microchannel layer adjacent to the heat transfer interface. This layer must remain thin because the temperature gradient on the fins reduces the cooling ability of the fluid flowing furthest from the heat acquisition interface. In contrast, in the normal flow arrangement, the flow can occupy the entire area of the cold plate. Flow velocities are an order of magnitude lower in the normal flow configuration than in the parallel flow configuration.
- ***Short flow passages.*** In the parallel flow arrangement, the flow passage length is determined by the size of the device being cooled. This length can be as much as 2 cm in high performance processors and even larger in high capacity IGBTs. In contrast, in the normal flow arrangement, the flow passage length is independent of the size of the device being cooled and can be chosen to optimize the performance of the cold plate. Since most of the heat transfer takes place in a thin layer close to the heat acquisition interface, the flow passages in the normal flow arrangement are typically an order of magnitude shorter than in the parallel flow arrangement.

These characteristics of the normal flow arrangement endow the NFHS with the advantages highlighted in Sections 2 and 3, namely:

- ***Excellent thermal performance.*** Low fluid velocities combined with short flow passages allow the use of very narrow passages without incurring excessive pressure drop. Narrow passages, in turn, increase the surface area per unit volume and the fluid heat transfer coefficient. As was shown in Section 3, the net result is that a normal flow heat sink excels in all three key performance paramenters: the NFHS can simultaneously achieve very low resistivity, low pressure drop, and high thermal effectiveness. The high thermal effectiveness results in low flows. Low

flow rates and high fluid exit temperatures greatly simplify the design of the remainder of the thermal management system.

- ***Ability to eliminate "hot spots".*** The independence of the local heat transfer from the heat transfer in other regions of the cold plate makes it possible to optimize the performance of the cold plate by tailoring the local resistivity to the heat dissipation profile of the device being cooled. As shown in the design example in Section 2, tailoring the cold plate resistivity is a very effective means for eliminating "hot spots" and, in addition, it can result in a several-fold increase in cold plate effectiveness, and reduction in flow rate and pressure drop.
- ***Compact size and low cost.*** The very low resistivity possible with the NFHS, coupled with the ability to tailor the local resistivity, eliminate the need to use heat spreaders. The footprint of the NFHS need not be any larger than that of the device being cooled. The small size of the NFHS cold plate will enable the designer to increase the packing density of the electronic components and will also reduce the cost of the cold plate. In fact, in devices having a hot spot surrounded by lower heat dissipation areas, it may be advantageous to use a heat concentrator to further reduce the size and cost of the cold plate.
- ***Performance independent of size and geometry.*** Since the length of the flow passages and the local fluid temperatures are independent of the size of the device, the NFHS can be used to cool devices of arbitrary size and geometry.